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A measurement of the extent of the color-sensitive areas of the retina and of the wavelengths of light stimulating the respective receptor mechanisms

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A MEASUREMENT OF THE EXTENT OF THE COLOR-SENSITIVE AREAS OF THE RETINA AND OF THE WAVELENGTHS OF LIGHT STIMULATING THE RESPECTIVE RECEPTOR MECHANISMS

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PREFACE

The interest of the writer was directed toward the phenomena of color vision in 1927 as a result of attending concurrently two courses in the University of California touching upon the subject, but treating it quite differently, with results far from mutually consistent. Prof. R. S. Minor, in his course on physical optics, discussed color vision from the physicist's standpoint, making use of the Young-Helmholtz theory; while Prof. G. M. Stratton gave the psychological treatment, based upon the Ladd-Franklin theory, as a part of his general psychology. Several of the more obvious points of conflict impressed the writer so strongly that he was led to bring the matter to the attention of the professors concerned. At the resulting conference between the two, a number of demonstrative experiments were performed, and from the discussion of these in terms of the various theories the writer profited much. However, many facts remained unreconciled, so the writer resolved to investigate the subject further should opportunity present itself. The following research is a beginning of that study.

The writer wishes to express the highest appreciation of

of the thorough cooperation given by Prof. Samuel R. Cook, not only in the matter of helpful suggestions, but particularly regarding the material requisites for carrying on the work.

The writer also acknowledges his indebtedness to Dr. Calvin J. Looser, of Lodi and Berkeley, for the perimetric color-field measurements which he was good enough to take as a check upon the experimental results.

Thanks are also due Professors J. William Harris and G. R. Pease for a number of pertinent criticisms and suggestions.

Finally, the writer wishes to thank the several members of the faculty and student body of the College of the Pacific who, by serving as the subjects for rather tedious measurements, made this research possible.

CHARLES A. RINDE

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INTRODUCTION

The problem of colors and color vision is one that would naturally come to the attention of man long before the dawn of the scientific era. For the differences in appearance of the various objects making up his external environment arose in no small measure from the striking variation in what we call "color." Yet, despite its conspicuouness from early times, the phenomenon of color was not among the first to be successfully attacked under the new scientific method. Indeed it was almost exactly two centuries after Galileo fathered experimental science that the earliest attempts were made to unravel the complexity of color phenomena. For in order that work along this line should be fruitful, it was necessary that an adequate theory of light itself should have preceeded it.

In 1801 Thomas Young built the needed foundation by reviving the undulatory theory of light and subjecting it to the crucial test of interference.[1] It is highly significant that in the same year he began the studies which resulted in a theory of color vision[2] which has persisted, not without alteration in many particulars, to be sure, until the present day. But the central idea around which Young formed his theory, tri-receptorism, is still the basis

[1] F. Cajori, A History of Physics, p. 140.

[2] F. Cajori, op. cit., p. 185.

of the color theories most generally held.[3] According to this tenet the light corresponding to the primary color sensations, whatever the number of these "primary colors," acts upon three kinds of nerve endings. In the original theory as advanced by Young each nerve ending corresponded to a single color range.[4] This has been modified until, as is now generally taught in elementary psychology,[5] there are held to be two chromatic responses given by each of two receptors, leaving the achromatic or black-white response for a third. The present theory, assembled by Dr. Christine Ladd-Franklin after a close scrutiny of the previous and contemporary theories, allows red and green to correspond to one receptor and blue and yellow to the other.[3]

The Object of This Investigation

It is, then, the purpose of this research to discover facts which would tend either to verify or to confute the present theory. To this end the writer thought it fruitful to measure the sizes of the fields in the retina responding to various wavelengths of nearly mono-chromatic illumination. For it is very well known that only a limited region of the retina is color sensitive,[7] and that the extent of the region sensitive to one color may differ from that sensitive to another. In other words, if any given color consisting of a narrow range selected from the spectrum is brought in from the edge of the field of view while the eye remains fixed, the image will move inward on the opposite side of the retina, producing first an achromatic sensation, then a sensation of color when the image falls within

[3] See Chapter I of this paper.

[4] Helmholtz, A Treatise on Physiological Optics, II, 426.

[5] R. S. Woodworth, A Study of the Mental Life, p. 221.

an appropriate color field.

Now let us suppose that there are certain primary colors which we shall name A, B, and C. By saying that A is a primary color I mean simply that A corresponds directly to one single sensation and not to a mixture of sensations. If it can be found that light of a certain wave length produces the color sensation A and no other, then A is clearly a primary color. But this may turn out to be difficult and uncertain if the mere judgment of the observer is allowed to remain the determining factor, for it is not at all easy to decide whether any givén sensation is simple or complex. Let us now assume that the color fields A and B are of different sizes, A being, say, the larger - a fact which can be determined either by our measurements or by the usual perimetric method in common use by optometrists. Then if an image having some color corresponding to a wavelength between A and B, call it AB, be moved inward slowly from the outer limit of vision, it will arrive first in a region giving no color effect, then it will reach an area in which it produces the sensation corresponding to A, and finally to a space where B is also affected, producing the mixed sensation AB. It is obvious that if this change in color is noted by the observer, the outer one must be the primary and the inner the mixed sensation.

[4]Helmholtz, A Treatise on Physiological Optics, II, 426.

[5]R. S. Woodworth, A Study of the Mental Life, p. 221.

If the wave length can now be changed in the direction of A until the change of color from A to AB no longer occurs, the only sensation will be that of A. Furthermore, one of the limiting wavelengths to which the sensation mechanism of primary color B responds will have been determined. The same reasoning may now be applied to another set of color fields.

The Significance of the Sizes of the Color Fields.

If certain pairs of colors, say M and N, and U and V, are respectively supposed to belong to two receptor mechanisms X and Y, and if the areas affected are not all of the same size, then the areas reacting to M and N - or more accurately, the areas giving the M and N sensations - should be very nearly equal or should, at least, vary simultaneously; i. e. in cases of a large M field we should expect a correspondingly large N field, etc. But we should conversely anticipate that there would be no such relationship between the fields of M and U or any other two which are not a pair belonging to a single receptor.

The object of the present research is then to explore the color fields with mono-chromatic light - i. e. light containing a narrow range of wavelengths, in the hope that some slight increase in the knowledge of color vision theory might possibly result.

The Apparatus and Procedure

The source of light was an electric arc of the vertical projection type, operated on a direct current of forty-five amperes so as to produce slightly less than two thousand candle power. A pair of condensers were used to bring the beam to a rough focus at a distance of about sixteen inches from the lamp, and at this point was a shield of heavy copper designed to dissipate the excessive heat. A slit about one third of a centimeter in width permitted light to fall upon a narrower vertical slit provided with a micrometer screw adjustment. The latter slit served as the source of white light for a diffraction grating, the light being rendered parallel by the usual achromatic collimator lens system. The first-order spectra thus produced were each approximately thirty centimeters in length at a distance such that the intensity was satisfactory. Here one spectrum was thrown upon a mat containing a vertical slit two millimeters wide. The range of color thus selected, one one-hundred-fiftieth of the spectrum range, was permitted to illuminate an opal-glass disc visible to the observer.

The whole apparatus, including the disc, was mounted upon a heavy table capable of being rotated about a vertical axis passing through the eye of the observer; and the whole grating system was mounted separately so that the spectrum could be moved over the final slit to any desired color. The spectrum was measured on an arbitrary scale having two hundred sixty divisions and was afterward calibrated in wavelength by the spectrometer-and-grating method with a maximum error of approximately four tenths of one per cent, this accuracy being found ample to make the errors introduced at this point entirely negligible compared to those arising in other parts of the experiment. The angular position of the observed disc was measured upon a large scale calibrated in tenths of degrees to thirty-six degrees each side of the central position.

In performing the experiments the observer was placed within a neutral-gray semi-circular booth from which all extraneous light was carefully excluded and instructed to fix one eye upon a slightly illuminated gray disc while watching for the first appearance of color or any changes as the opal glass with the chosen spectrum color was brought slowly in from the extremity of the field of view.

The data recorded were the arbitrary wavelength, the angle, between the fixation point and the color disc, at which various colors and color changes were observed, the name of the subject, the eye or eyes used, and various unexpected or exceptional phenomena that might be observed.

As a check on this work some eighteen thousand readings of the sizes of the color fields, as measured on a perimeter having pigmented targets, were taken in the green, red, and blue by Mr. Calvin J. Looser, O. D.; and the results of this work will also be included in the present paper.

CHAPTER I

A BRIEF REVIEW OF SEVERAL OUTSTANDING CONTEMPORARY COLOR THEORIES

The Young-Helmholtz Theory

When originally advanced by Thomas Young, the theory provided for three color-receptor mechanisms, sensitive to red, yellow, and blue, respectively.[6] But Wollaston's discovery of the dark absorption lines in the solar spectrum, together with the suggestion that these were the dividing lines between the primary colors, led Young to alter his choice to red, green, and violet or blue. This tends to justify von Kries' opinion that Young's work was rather more conjectural than experimental.[7]

The present theory, the result of extensive modification by Helmholtz and his assistants, accounts for all chromatic sensations in terms of three primary colors, i. e. "light stimuli ... may be completely represented as a function of three variables."[8] This leads to the adoption of the view that there are three distinct color mechanisms, and three only, a tenet which holds its place even in the most recent color theories, under the name of tri-receptorism.[9] The three sensations were named red, green, and blue, but the "red", as shown by Koenig's resonance curves,[10] has its maximum definitely in the yellow at a wavelength of .565 microns, the "green" was also shifted a little toward the yellow, being at .550; while the "blue" maximum was at .450 microns, slightly toward the violet.

6,7,8,9,10 Please turn to page two.

The Aubert-Hering Theory

Four colors are provided for in this theory, and the sensation white is admitted as a separate primary sensation, a fact which is largely responsible for its favor among the psychologists. Aubert stated that pure red and pure green are complementary, i. e. they result in white when mixed. This is not true, for repeated experiments by the writer have always led to the production of yellow by any mixture of colors red and greed. In fact, it is necessary to get so far from "pure red" and "pure green" in order to produce white that even inferior high school students immediately recognize the colors as "blue-green" and "purple" or "lavender." This fact is also criticised by Ladd-Franklin[11].

J. von Kries also points out that this theory "has not been adequately tested as to the very points most easily investigated," [12] refering, of course, to the nature of the "pure colors."

[6] F. Cajori, loc. cit.

[7] J. von Kries, Commentary in Helmholtz, op. cit., II, 426.

[8] Helmholtz, op. cit., II, 426.

[9] Cf. Ladd-Franklin theory later in this chapter.

[10] Helmholtz, op. cit., II, 463.

[11] C. Ladd-Franklin, Color and Color Theories, p. 47.

[12] J. von Kries, op. cit., II, 434.

The Ladd-Franklin Theory

The theory advanced in 1893 by Christine Ladd-Franklin, after having undergone lavish amplification and extension at her hands meanwhile, is now by far the most inclusive. It is difficult to determine whether it should be regarded as a four- or a six-color theory, but it is definitely an evolutionary theory based upon tri-receptorism.[13] She assumes that there are four primary chromatic sensations, excluding the black-white-gray series, and that these, as already stated are in pairs, viz., red-green, and blue-yellow, each pair belonging to one receptor. The early foundation sensation, she supposes, was achromatic or "toneless" white. This soon developed into a differentiated sensation for the two halves of the spectrum, giving blue and yellow. The yellow next subdivided to give the red and green. The action is all explained in chemical terms by assuming that the first sensation was due to a molecule capable of breaking down in one manner only, when acted upon by light. This in the processes of development finally became more complex and thus capable of decomposition in two different ways to the light from the two halves of the spectrum. The further development of the long-wave half led finally to differentiated decomposition of the portion formerly giving yellow so as to produce red and green. This explains complementary yellow-blue and yellow-forming red-green beautifully by assuming that

[13] C. Ladd-Franklin, op. cit., p. 284, under Tetrachromatic. also The Physicist and the Facts of Color, Science, LXVI, 589, 1927.

when both the colors of any pair are present, there is immediate recombination, so that the reaction takes the path belonging to the preceding stage of development.[14] There are also simple and apparently rational explanations of many other phenomena of visual sensation, including such as positive and negative after-images, color-blindness, twilight vision, etc. The bearing of this theory upon the present thesis is, however, not along these lines but merely concerns the primary color sensations and the color fields. This has already been outlined in the Introduction.

Two Photo-Electric Theories

Eight years ago Janet Clark at Johns-Hopkins University put forth a theory dependent upon the emission of electrons from the rods and cones. This action was supposed to be no more than the well-known photo-electric effect in which the velocity of emission of the electron is proportional to the frequency of the radiant energy from which it results, and is entirely independent of intensity. Miss Clark makes use of this in explaining color sensation by assuming that these free electrons move through the pigmented material surrounding the rods and cones until their original velocity is spent, when they come to rest and form with the rods and cones electro-static capacities similar to the charges on a Leyden jar. Since the capacity is dependent upon the distance between the electron and the rod or cone, and since this distance is determined by the initial velocity, we see that this capacity will be an inverse function of the

[14] C. Ladd-Franklin, op. cit., 66 - 71; 126 - 31; also Tetrachromatic Vision and the Genetic Theory of Color, Science, LV,555, 1922.

of the frequency. This capacity then is a function of the color of the impinging light, and it is merely necessary to suppose that it in turn determines the velocity or frequency of a current passing to the cortex. Miss Clark insists that it is not important to her theory whether this current be a single impulse or an oscillation.[15]

This would seem to indicate an infinite number of primary colors unless it could be assumed that the electrons stop in a certain number of homogeneous layers, and this does not seem compatible with the energy relations involved. This theory would seem to make the present research useless, then, if correct.

In addition the explanation of white involves a considerable strain.

Dr. Fritz Schanz has advanced a very similar theory, except that he has the electrons emitted from the pigment of the pigment epithelium. They are then received at velocities proportional to the frequency of the incident light, and thereupon travel as direct currents to the cortex. It is supposed that in all cases where chromatic effects result that the electrons retain their characteristic velocities, but that when white is produced the electrons of various speeds so interfere with one another on the way that they arrive at the cortex at some average velocity and produce the achromatic sensation.[16] This is very difficult to reconcile with

[15]Janet H. Clark, A Photo-Electric Theory of Color Vision, The Journal of the Optical Society of America, VI, 813.

[16]F. Schanz, A New Theory of Vision, Am. Jour. of Physiological Optics, IV, 284, 1923.

present knowledge of electron flow in conductors. Any treatment of primary colors from the viewpoint of this theory would be very difficult.

The Cook Electromagnetic Theory

Professor S. R. Cook has recently outlined an electromagnetic hypothesis[17] which seems not only capable of accounting for many of the facts of color sensation, but which also offers for the first time a satisfactory explanation of the structure of the retina. The contention of this theory is that light energy which impinges upon the rods and cones in the form of an electromagnetic wave motion does not depend upon any photo-electric or chemical action for reception, but simply produces in the receptor system a high-frequancy electric oscillation. The rods are then held to be "broadly tuned" - i. e. their resistance is high compared to their inductance and capacity - so that they receive, and oscillate to, the whole visual range of wave-lengths, producing, whenever they oscillate to energy of any wave length, the single sensation of white. The cones, on the contrary, oscillate to only a narrow range of wave lengths. When one of the fundamental wavelengths is produced, the cone system having the proper inductance and capacity oscillates and transmits this oscillating current to the cortex. A frequency not quite of the fundamental frequency, but within certain limits, may cause this same cone system to oscillate, and have a similar effect upon another.

[17] Dr. S. R. Cook, <u>On the Electromagnetic Theory of Sight and Color Vision,</u> May, 1930, unpublished.

The result would be interpreted in the cortex as one of the mixed colors.

The results of this research will be treated largely from the standpoint of Dr. Cook's theory, not because of proximity, but solely for the reason that it appeals to the writer as offering a thoroughly plausible background for the explanation of the observed phenomena.

Since it is not at all the purpose of this paper to convert itself into a symposium on color theories, but merely to make use of these in so far as they affect the explanation of the results at hand, let us pass on to a consideration of these data. However, our remarks on color theories would be incomplete without calling attention to the fact that none of the foregoing theories are more than hypotheses, as yet untested, and the whole field of color vision is one of contention and confusion.

CHAPTER II

MEASUREMENT OF THE FIELDS OF THE SIMPLE COLORS

A "simple" or "primary" color means here merely the color corresponding to an homogeneously chromatic illumination which undergoes only one change in the color sensation produced as the illumination falls on different regions of the retina. This change is from the achromatic to the chromatic sensation as the image is moved inward from the edge of the field of view. Take the case of green as an example. Let the eye of the observer be fixed upon the fixation point, and let the colored disc illuminated by a narrow range of the spectrum be brought slowly inward along the arc of a circle. At a certain definite point the observer will notice the appearance of the green color and the angular distance from the fixation point will now give approximately the angular size in this direction of the field sensitive to green. Now suppose that we alter the wavelength, say lengthen it, then the illumination may stimulate some other field if there is in that direction ~~the field of an ajacent color whose~~ an adjacent color whose field is larger than that of green. Thus the observer would call the name of this color before that of the green or of the combination of this color with the green. Obviously, except for a few carefully-selected colors this will represent the general condition. In fact, it was in this way that the yellow field was first noted to exist.

Two general classes of field measurements were made, viz., with diffraction spectral illumination as outlined in the Introduction, and with discs painted with carefully chosen pigments and illuminated by the "whitest" obtainable incandescent lamp. The first method is the only one applicable to the measurements requiring homogeneous and variable colors, but it has the disadvantages of being rather slow and also of being restricted to the horizontal meridian through the fixation point, unless the apparatus is to become rather complex and costly. The second has the advantage of speed and adaptibility to field measurement along any meridian, making it possible to take a large number of values for statistical purposes.

The second method is made use of here merely as a check upon the more carefully analyzed results from the use of the first. The original data consisted of three independent readings or more for every measurement made by the first method; thus making possible the elimination of erratic results due to mistakes, and a constant checking of the consistency of the results.

For obvious reasons the mass of data is not to be included in this paper, but will be kept available for anyone wishing to peruse it. The final results will be treated in the following ways: by averaging the fields of each color for all the eyes measured, by finding the differences in the field sizes and averaging these differences for the ~~four~~ six possible pairs of the four fields measured, and by studying the distribution of sizes for the four fields.

Color	Wavelength Microns	Number Measured	Average Size in Degrees
Green	.528	72	14.61
Red	.640	71	15.48
Yellow	.590	45	18.33
Blue	.463	63	20.03

TABLE I

The table above indicates superficially that each of the four color fields is independent of the others in size. But it is open to the objection that the differences are too small to be conclusive for so small a number of cases - a total of slightly over 750 satisfactory measurements.

The reason for the rather small differences is that any appreciable proportion of abnormal eyes having the larger fields unduly small would decrease the totals for these fields. To escape this difficulty partially, it was found advisable to take the differences for each pair of colors for each eye measured, and then average these differences regardless of sign for each pair. This gave the values found in Table II.

It should be entirely clear from this table that no pairs of fields show themselves to be appreciably closer in size than the other pairs. Therefore we should be in a position to say that in any characteristic in which extent of field is involved there are no related pairs of fields indicated.

Color Pair	Average Difference Degrees	No. of First Larger	No. of Second Larger
Red-Green	3. 2	49	21
Yellow-Blue	4 .3	31	10
Yellow-Red	4 .2	30	19
Blue-Green	5 .3	42	24
Blue-Red	4 .2	36	31
Yellow-Green	5 .7	39	12

TABLE II

The numbers in the fourth vertical column represent the number of times the first-named field was definitely larger than the second; thus there were 49 red fields definitely larger than their corresponding green fields. The reverse condition is indicated by the figures in the last column on the right. Now it is important to note that, while all the satisfactorily-measured simple fields were used to determine the average differences in size, only those pairs whose difference was well outside the limit of experimental error were used in the last two columns.

Treating the whole number gives us the following table; which gives a more accurrate account of the situation than did the previous figures:

Color Pair	Percentage of the Total Number of Pairs		
	First-Named Larger	Second Larger	Roughly the Same
Red-Green	47	26	27
Yellow-Blue	46	24	30
Yellow-Red	69	10	21
Blue-Green	61	10	29
Blue-Red	56	24	20
Yellow-Green	80	15	5

TABLE III

It will be noticed that here all the figures for "Roughly the same", which was within a limit of about twice the probable error, are all about of the same magnitude until yellow and green are compared. But this is to be expected when we are comparing one of the larger fields with the smallest one. A similar result should have been expected for the blue-green had it not been for the fact, as shown by our perimetric check-up, that there were among our subjects an unduly large percentage of very decidedly contracted blue fields. The important point, however, is that Table III does not indicate the existence of any closely related pairs.

The next angle of attack will be a study of the distribution of the field sizes. To do this it will be necessary to divide the whole range of field sizes into increments of two degrees and plot for each color a curve of the number of fields whose sizes fall within a given increment against the central value of the increments. This graph is shown in Figure 1, page 13.

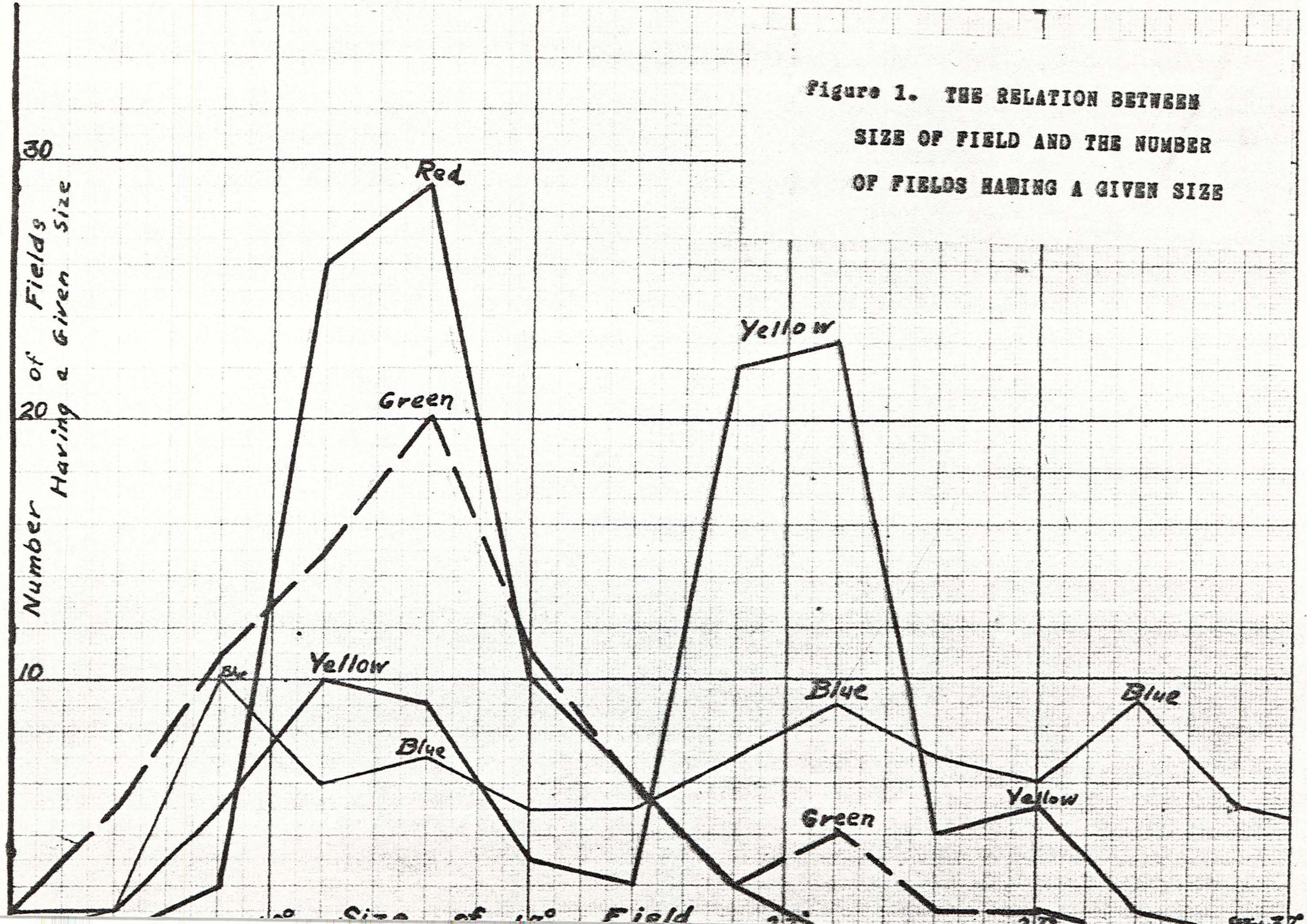

Figure 1. THE RELATION BETWEEN SIZE OF FIELD AND THE NUMBER OF FIELDS HAVING A GIVEN SIZE

It is seen that the red fields give a clean-cut probability curve with the mode in the vicinity of fifteen degrees. The yellow has a maximum at twenty-three degrees, but also a lesser one for fields approximately the size of the reds. The green has a maximum at the same size as the red, thus showing that the average tendency over many eyes is for these two fields to be rather close. But this would be misleading if interpreted to mean that in a given eye this tendency exists, for our data show that not to be the case. The explanation of the lower yellow maximum probably lies in the fact that a few persons whose yellow sense was rather weak, but whose red sensibility extended abnormally far down the wavelength scale, did not observe the yellow until the red field was also stimulated slightly by the light. The same type of reasoning might be made to explain the lesser maximum of the green. The blue fields were too scattered in sizes to make a significant plot.

The foregoing, then, leads to the conclusion that there are at least four primary color sensations corresponding very approximately to the wave lengths given in Table I, page 10.

The Sizes of Three Color Fields Measured by Perimetry

The angles in this case were measured by moving a painted disc toward the fixation point along a graduated arc designed to be rotated about the fixation point as an axis, into any meridian. The measurements were made at every forty-five degrees beginning with the horizontal meridian at the experimenter's right (on the subject's left), and proceeding counter-clockwise for successive readings.

A total of seven hundred seventy-three eyes were measured in this manner for the color fields red, green, and blue on eight meridians, making a total of 18,552 measurements. These data gave the average sizes of the fields for all meridians as follows:

Green	16 degrees
Red	22 degrees
Blue	30 degrees

This surely does not indicate a close regional relationship between the red and the green. The magnitudes will be noticed to differ somewhat from those previously given, but this is not surprising in two proceedures so radically different and at the same time concerned with so many variables. It is sufficient that the general proportions are the same, and the order of sizes is the same as already determined.

The average values for each color on each meridian need not be tabulated here, but are used to plot the color fields from eighth points, giving the characteristic set of color fields of Figure 2.

It is to be regretted that the measurement of the yellow was begun so recently that there are too few available to render a treatment here worth while.

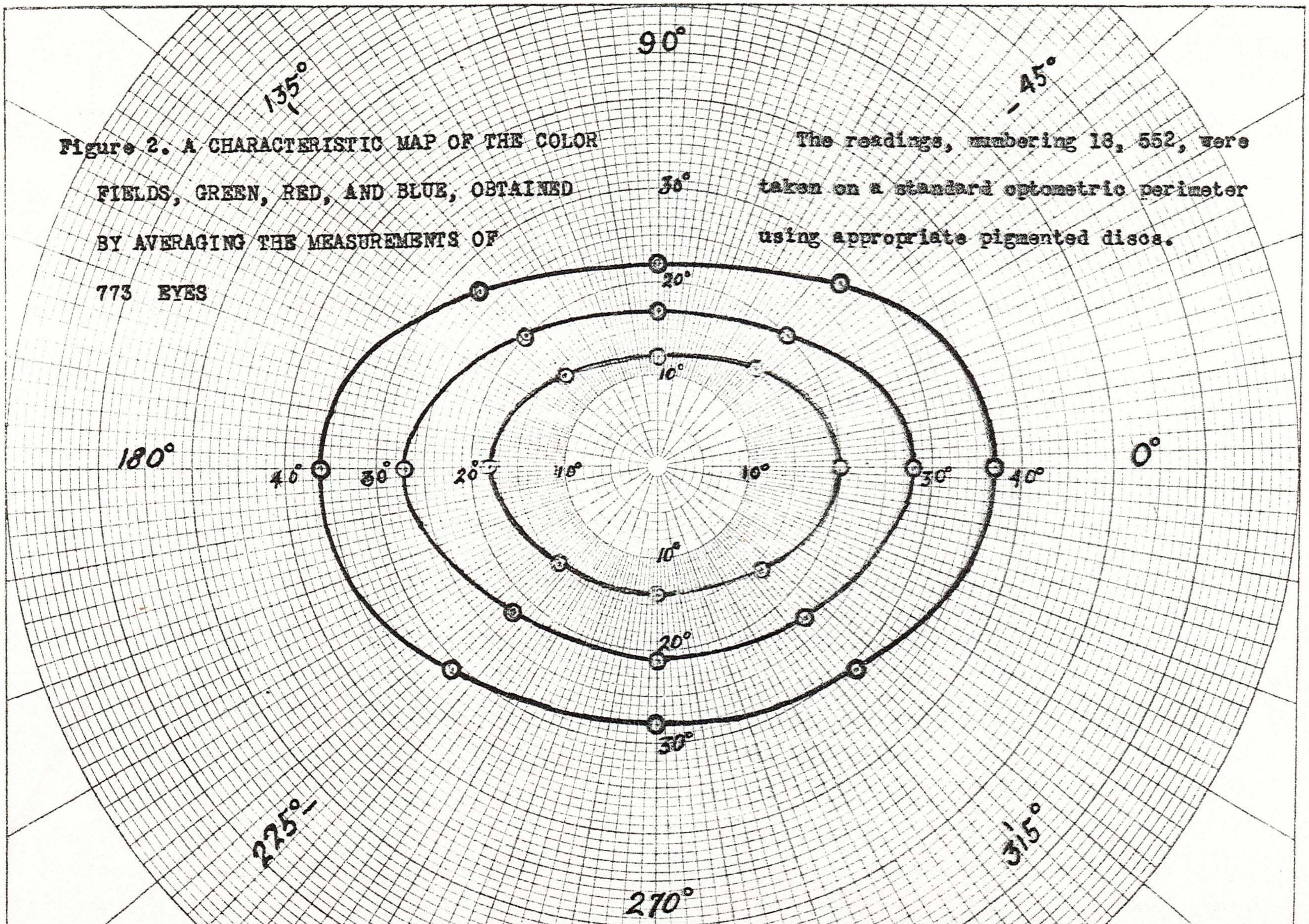

Figure 2. A CHARACTERISTIC MAP OF THE COLOR FIELDS, GREEN, RED, AND BLUE, OBTAINED BY AVERAGING THE MEASUREMENTS OF 773 EYES

The readings, numbering 18, 552, were taken on a standard optometric perimeter using appropriate pigmented discs.

CHAPTER III

A STUDY OF "COMPOUND" COLOR EFFECTS

The problem of mixed colors has heretofore been attacked chiefly from the standpoint of two or more mixed wavelengths producing a mixed sensation. It appears to me a necessary simplification to measure the effect of one narrow band of homogeneous wavelengths stimulating two different color sensations to varying degrees.

This phase of the investigation will serve at least two purposes. It will show us the limits of wave length capable of stimulating each of the color sense mechanisms, and it will give us an idea of the relation between extent of color field and wavelength.

The study of these compound fields involves the measurement of two color fields, and therefore the production of two color sensations which are mixed when the imaged has reached the smaller field. Thus a color may be chosen having a wavelength somewhere between that corresponding to blue and that corresponding to green. Suppose now that blue is the larger field. The first color interpretation as the disc is moved inward will be blue, but when the disc reaches the inner field, the color sensation will be changed to blue-green by the adding of the green sensation to that of the blue. This process at various wavelengths gave the curves in Figure 3.

The wide range of the yellow, and its very sharp cessation are particularly evident. This applies also to the green, and it

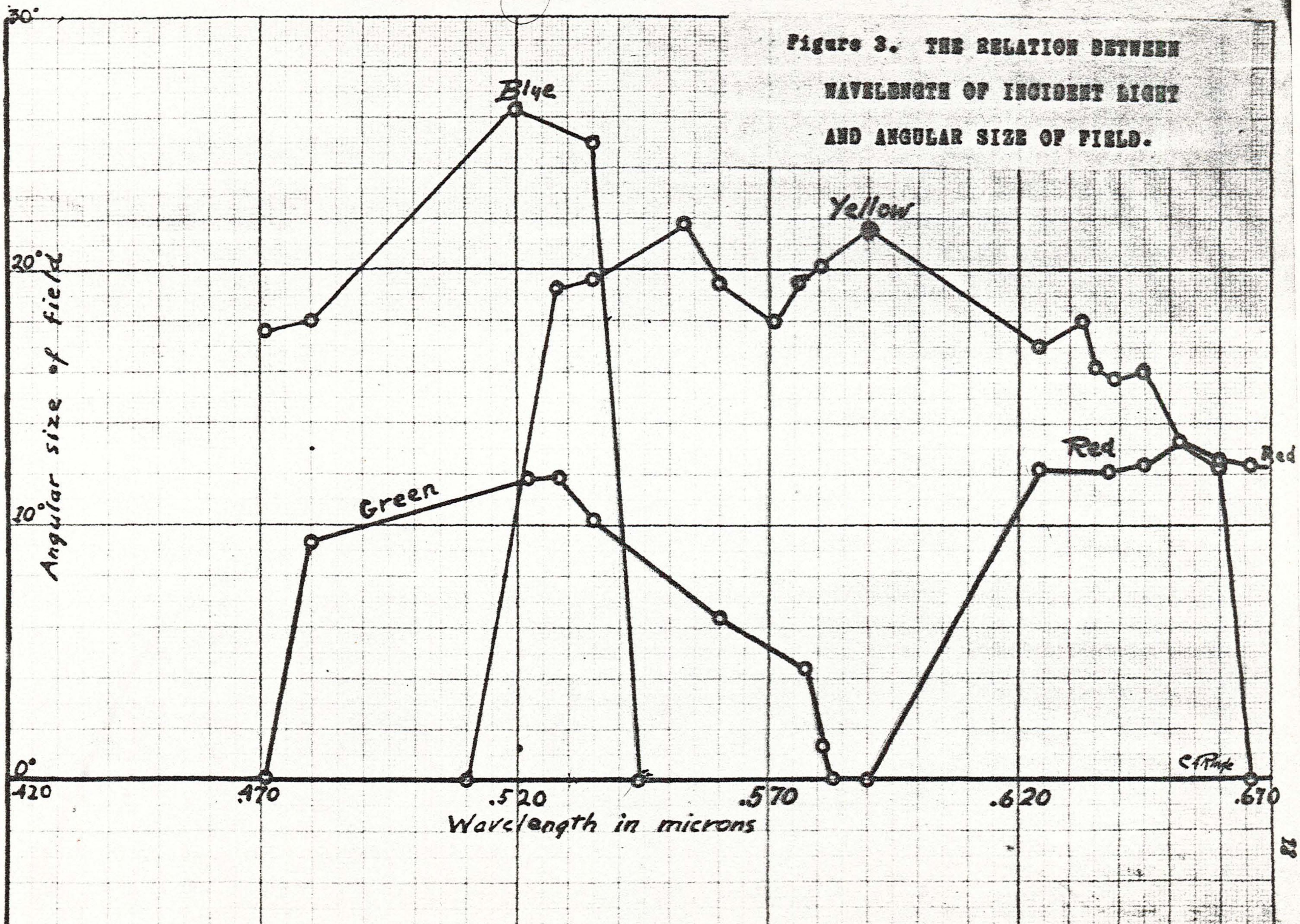

Figure 3. THE RELATION BETWEEN WAVELENGTH OF INCIDENT LIGHT AND ANGULAR SIZE OF FIELD.

is the writer's opinion after a careful consideration of the data that this latter curve is most nearly characteristic. It is also worth observing that at certain wave lengths in the green, three color changes are possible, viz., at the boundaries of the blue, yellow, and green, respectively. These changes have actually been observed experimentally.

The blue curve, however, is decidedly unsatisfactory and requires further investigation. In addition, the lower end of the spectrum appears out of symmetry with the opposite portion. The green is clearly in the central region, the blue and yellow are roughly symmetrical so far as the former has been carried out. But there appears no inner field in the short wavelengths. Now, furthermore, from the foregoing explanation of the production of mixed color sensations by the action of a single homogeneous color upon two color mechanisms, it is clear that when the wave length has passed below the lower limit of the green no further change will be possible. For it is another result of these observations that when one color mechanism is stimulated, say the yellow, the sensation is always of the same chromatic quality regardless of the wave length, so long as there is no mixture. Then from wavelength .471 micron in this case, downward there should be no appreciable change in the chromatic quality. And this is distinctly contrary to fact.

For this reason and from the considerations of symmetry, we may therefore conclude that there is another primary color field as yet undiscovered. And let us tentatively name this the "violet." And by violet is not meant that abominable mixture of red and blue, usually called purple, which has so blinded Dr. Ladd-Franklin and her offspring[18] as to preclude for them the possibility of a pure color in the lower part of the spectrum.

From here I suggest a point of departure for additional research in this subject, and that should be an attempt to determine whether or not this additional color field exists.

[18] C. Ladd-Franklin, The Physicist and the Facts of Color, Science, LXVI, 591, 1927.

CHAPTER IV

A BRIEF NOTE ON COLOR SENSE DEFICIENCY

The whole subject of color-blindness is replete with facts immediately relevant to any study of the color fields. But, unfortunately, such information as is available in this field is so much the subject of controvery that little can be regarded as firmly established. Hence it is useless to search in this direction for evidence tending either to substiantiate or contradict the results of the present research.

So it was evident from the outset that to embark upon any side investigations into the nature of this sensory deficiency would be futile with the time and means now available.

However, one subject who was otherwise reliable demonstrated an inability to distinguish red and green. It was found that when allowed to indicate the colors of various regions in a spectrum about fifty centimeters in length, he gave the following series:

RED --- ORANGE --- YELLOW --- BLUE --- VIOLET

Now, the difficulty immediately arises that his sensations may be entirely different from those ordinarily meant by the names used. It is obvious, for example, that if a peculiar shade of brown had always been present for him when others spoke of orange, he would soon learn to attach the name "orange" to that particular brown. So the ability to name the colors is commonly known to be no real test.

But let us consider the field measurements in the light of the curves of Figure 3. The data obtained were as follows:

Wavelength of Illumination Microns	Usual Name	Subject's Name	Size of Field in Degrees Right Eye	Left Eye
.642	Red	Red	16.1	13.2
.590	Yellow	Yellow	24.5	21.8
.604	Orange	Red	21.2	17.5
.528	Green	Yellow		19.3

Clearly the yellow obtained at .528 microns is the same as is usually encountered first in testing the yellow-green at this point. The green is undeniably absent, but this was not unexpected as the fact that there was some defect of the red-green sensations was known from the beginning. The blue, however, might be expected to function if it were perfectly normal; yet no real defect of the blue is indicated for the reason that many normal blue fields do not begin to be stimulated until a much lower wavelength is reached.

The sensation produced at wave length .642 would necessarily have to be either red or yellow, or a combination of those two, if there has not been some entirely new color field added as a part of the abnormality, a most improbable phenomenon. And since the yellow field appears of normal size and is apparently normally interpreted at .590, the yellow alternative at .642 is eliminated. Therefore, unless unassailable proof to the contrary can be brought, it is rational to assume that red vision is normal at this wavelength. But the red field is far from normal because it becomes strikingly large, apparently obscuring the yellow, at wavelength .604 where the size of the red as measured by the production of orange is ordinarily decreasing. It seems possible that through some defect of the red-green sensory mechanisms the two senses have coalesced in such a manner as to raise the wavelength range to which the green responds to such an extent that at a wavelength as low as .528, which is ordinarily very nearly in the center of the wavelength range to which the green mechanism is sensitive, no stimulation of the green mechanism is produced. The abnormally low range of wavelengths at which red is found may be explained by assuming that the two fields are acting together, and this assumption would also explain the confusion of the longer wavelength greens with the reds.

There has been observed also a case in which the red was promptly interpreted as black. Unfortunately, no further measurements than this have been made, but it is, nevertheless, worth mentioning that Figure 3 indicates that if the red light is of a wavelength above that of the long-wave limit of the yellow, it will be the only color sense stimulated. Now if the red mechanism fails to respond, there should be achromatic illumination so long as the light falls in the region of the rods; but as soon as a region lacking rods is reached, the stimulation would abruptly cease, whereupon the sensation black might reasonably be expected. It appears that this is just what occurred.

As has already been noted, the work in this field is incomplete and the necessary verification resulting from a large number of measurements is entirely lacking. Therefore the above is intended chiefly as no more than material for interesting speculations which may suggest the subject matter for further investigation of color sense deficiencies.

CHAPTER V

SUMMARY AND CONCLUSIONS

To attempt the construction of a complete theory of color vision from the results of the measurements made in the course of this research would be folly of precisely the sort that has reduced the subject to its present condition. For these data are inadequate, both as to the numbers of observations and as to the variety of the phenomena investigated, to warrant such a procedure. The remainder of the paper will therefore be devoted to a brief summary of the facts, together with an indication of their bearing upon color theories.

I

The measurement of the simple color fields of the retina has brought out the following facts:

1. That there are certain definite wavelengths of homogeneous light which produce elementary sensations in measurable areas of the retina.

2. That these colors are at least four in number, and their wavelengths are roughly those of Table I, page 10.

3. That in any given eye the areas within which each sensation is produced are ordinarily all of different sizes, and there are no pairs.

4. That the results obtained by the perimetry of 773 unselected eyes are confirmatory for the three colors measured, green, red, and blue.

These lead to the conclusion that each of the four color receptors is a unitary system, independent of the rest except as a joint participant in compound effects. Therefrom it follows that not less than four chromatic, and one achromatic, color receptors exist, and this is contrary to the basic principle of the Ladd-Franklin theory, viz., tri-receptorism.

II

The data from the observations of compound color effects seems to contain the following indications:

1. That each of the receptor mechanisms functions over a relatively wide range of wavelength.

2. That these characteristic ranges overlap greatly, so that ordinarily two receptors may be stimulated by light of one homogeneous wave length.

3. That the size of ~~mf~~ field for each of the four primary colors is a continuous function of the wavelength, giving a graph resembling a sharply cut off resonance curve.

4. That there is a decided lack of symmetry in the positions of these ranges in the visible spectrum.

5. That, according to the present data, there is an- an apparent deficiency of one field to operate in the shorter-wavelength end of the spectrum.

Here we have the work in the establishment of the primary color sensations thoroughly substantiated. But in addition, it becomes clear that the intermediate shades, even though they are of homogeneous wavelength, are blends of these same primary sensations.

The independence of the mechanisms for red and green is further indicated by the observation of a case of color defect. From the fact that within the wavelength range where the red and yellow receptors operate, both were functioning, and from the further fact that there was chromatic sensation in the upper wavelengths, covered solely by the red, it is clear that the red receptor was being stimulated by the kind of light that normally acts upon it. But the absence of the green at the central region of its normal range, leaving only yellow at that point, together with the excessive extent of the red field, both in wavelength range and in size of field in the wavelengths near the lower limit of the normal red, added to the tendency to confuse red and green, lead to the following conclusions: Firstly, that the red and green fields have become united directly by some short-circuiting process. Secondly, that the lower limit of the green has been brought to a somewhat longer wavelength. Thirdly, that the result of stimulation of this consolidated field is interpreted indiscriminately as red over the entire range of the wavelengths covered by it, except as the combination with the yellow sensation produces orange in the normal manner. Lastly, that the green and the red receptors, being both stimulated by wavelengths all the way from the upper greens to the longer reds, ~~and~~ produce by this double reaction such intense stimulation as to completely mask the yellow in the central region of the wavelengths covered by the coalescent fields.

Points of Contact with the Theories

I

To the three colors of the Young-Helmholtz theory a fourth, yellow, has definitely been added. This is not a reversion to Young's original set of colors for the reason that red, green, and blue are all retained. Nor is it a negation of Koenig's discovery that the effects of all visual light stimuli may be reproduced in terms of three primary colors. For his experiments were along the lines of demonstrating the equivalence of physical mixtures, and there is no reason whatever for supposing that the "primary" colors for this purpose would have any particular relation to those of the receptor mechanisms. In fact, the red, green, and blue of the Helmholtz theory are not at all equivalent to the colors suggested for the primaries by this research.

Name	Helmholtz-Koenig Microns	From This Research Microns
Red	.565	.640-.670
Green	.550	.528
Blue	.450	.463

It is not to be implied from this comparison that the figures in the last column are to be considered precise, for it is quite obvious that they are only roughly approximate. It is expected, for example, from a consideration of the upper limit of the yellow in the curves of page 18, that further investigation will lead to the choice of the center of the red range as a longer wavelength, probably in the vicinity of .670 microns. But there is no indication that any of these modifications will lead to any closer correspondence between the two sets of colors, but rather the contrary.

II

Our colors are so manifestly not those of the Hering theory that there is no need for comparison. Regarding the less obvious implications of that theory, the present data is considered too restricted for application.

III

That the tri-receptorism upon which the Ladd-Franklin theory rests is incompatible with a satisfactory interpretation of our data has already been shown. But the inclusion of yellow as one of the primary sensations is corroborated, apparently beyond reasonable doubt. As to the limitation of these to four, however, there is an indication of error, our data indicating a very great probability of one other primary color sensation corresponding to a range in the extreme lower wavelength region.

IV

No clean-cut points of contact with the photo-electric theories is evident from a perusal of them, and an exhaustive treatment involving the more obscure parts of the theories themselves would be outside the scope of this paper.

V

As already stated the central idea of Dr. Cook's theory is that electromagnetic waves - of which x-rays, visible light, and the Hertzian waves of radio communication serve as examples differing only in wavelength - are capable of being absorbed by suitable conductors in the form of electric oscillations or alternating currents. These currents have not been produced experimentally in the higher frequencies, however, because of the difficulty in getting small enough conductors other than atomic or molecular. The condition for free oscillation is as follows:

The period is $$T = \frac{2\pi}{\omega} = \frac{2\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}}.$$

The wavelength is $$\lambda = \frac{2\pi c}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}}.$$

The frequency is $$f = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}.$$

Where L is the inductance, C the capacity, and R the resistance of the system of conductors; and where c is the velocity of propagation of the waves. (These three forms of a single equation are given merely because it is convenient to refer to any one of them without explanation.) The three quantities in the radical are determined by the physical characteristics of the conductors and by the surrounding dielectrics, and c is in addition dependent upon the refractive index of the medium through which the light is incident upon the retina.

Figures 4 and 5 show typical curves for the variation of current with frequency in a circuit of given L, C, and R. The effect

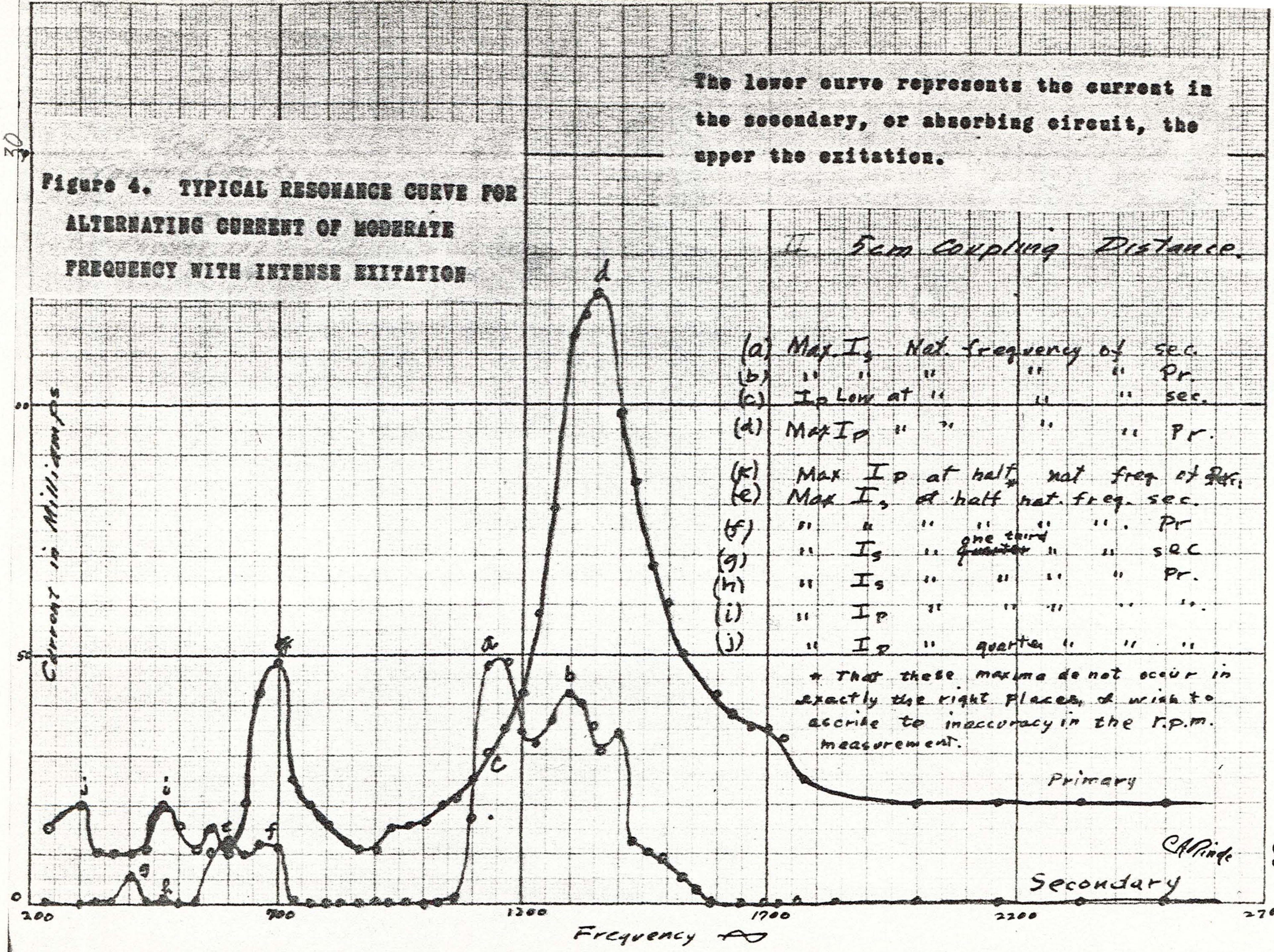

Figure 4. TYPICAL RESONANCE CURVE FOR ALTERNATING CURRENT OF MODERATE FREQUENCY WITH INTENSE EXITATION

The lower curve represents the current in the secondary, or absorbing circuit, the upper the exitation.

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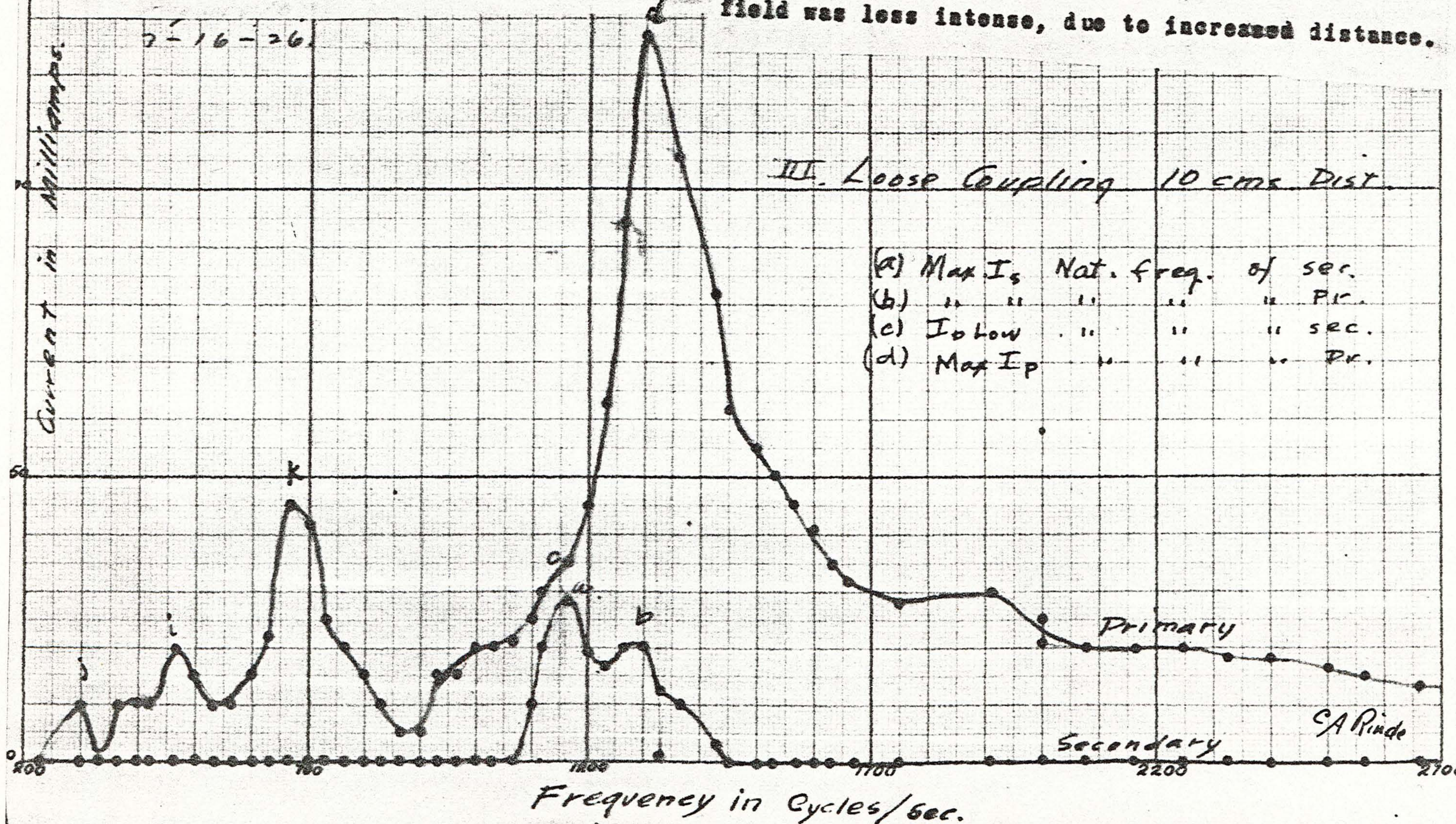
Figure 5. TYPICAL RESONANCE CURVE FOR ALTERNATING CURRENT OF MODERATE FREQUENCE

The lower curve represents the current in the absorbing or secondary circuit, the upper the excitation. This differs from Figure 4 in that the exciting electromagnetic field was less intense, due to increased distance.



31

of increasing L and C is to increase the wavelength and period, or to decrease the frequency. The effect of increasing R alone is to flatten the maximum and broaden the range of the curve.

Now we are ready to account for the shape of the curves on page 18. Let it be supposed that each of the areas in the retina possesses the characteristic; that near the outer edge of the color field in question there are units of the receptor mechanism which are progressively less completely developed, and therefore less sensitive, the farther they are from the center of the field. (Any evolutionary theory would be likely to contain this implication.) Then, if the receptor mechanism be considered as a system of conductors in which oscillation is taking place, we should expect that as the wavelength, or the frequency, is altered away from that of the maximum current, the current will decrease in such a manner as indicated by the lower curves in Figures 4 and 5. As the current decreases, the first mechanisms to cease functioning will be the outermost, or least developed. Thus, not only are the decreasing areas of the fields near the limitsof their wavelength ranges accounted for, but this effect is made indicative of the decrease of the current. Therefore, a resonance type curve should be expected for each field in Figure 3. (Note that in comparing Figure 3 with Figures 4 and 5 it must be born im mind that the number of points in the latter two makes a smooth curve possible, while this is not true in the former.) Comparison then shows our expectation fulfilled.

Furthermore, consideration of the curves of Figure 3 with due regard to the frequencies involved leads to the conclusion that the receptors are not very sharply tuned, i. e. the range of wavelength is relatively quite broad. This would allow for the moderately high resistance of the nerve fibres and other conducting parts.

The red-green color defect discussed in Chapter IV is also readily and satisfactorily explained by this theory. Suppose that in the mechanical arrangement of the parts of the two receptor mechanisms, red and green, there is a certain regularity that makes possible a short-circuiting, say in the retina, or in the pairs of conducting fibres leading to the cortex. Such a regularity even for large numbers of pairs of parts is by no means improbable - consider the patterns of certain shell fish. Then the inductance and capacity of the whole system would necessarily be raised, thus shifting the wavelength range of both systems toward the longer waves. The effect upon the lower would be relatively greater, while the shift of the upper would be decidedly less, and might even be negligible. But the increase in the amount of conducting material in the double sustem would greatly broaden its range.

Obviously, ~~since~~ the stimulus arising from the currents in the coalescent system would have to be <u>either</u> red or <u>green</u>, or some variation of one of them, but not both, for the sensation over the whole range of a single field has been found to be of one quality, and a pair of fields connected in the manner described would function as a single field. Which kind of sensation dominates might depend upon the same sort of factors as determine what is known to optometrists as the "dominant" eye. Of course, I have assumed here that there is a one-to-one correspondence between the stimulation of the mechanism and the sensation produced, and as this had better be left to the results of purely psychological research, let us leave the matter of the sensation itself purely as a conjecture.

The structure of the retina appears to be an additional justification for interpreting our results in terms of an electromagnetic theory. Remembering that four independent chromatic receptor mechanisms were found and that there was a strong indication of the possibility of a fifth, let us examine Figure 8. Here we see a set of five cones, which we will assume to be characteristic. From left to right, each is connected with a longer fibre leading to the ganglion cells. If this be considered as the portion of the circuit determining the wavelength of the oscillation, then each will function at a respectively longer wavelength because of the increased inductance, and to a lesser degree because of the increased capacity, resulting from the successively longer conductors. There is also apparent a single amacrine cell connected to each cone circuit at the synapse between the bipolar and the ganglion neurones. The lengths of these connecting fibres decrease from left to right, and they will, therefore, if capable of

Figure 6. THE STRUCTURE OF THE RETINA [20]

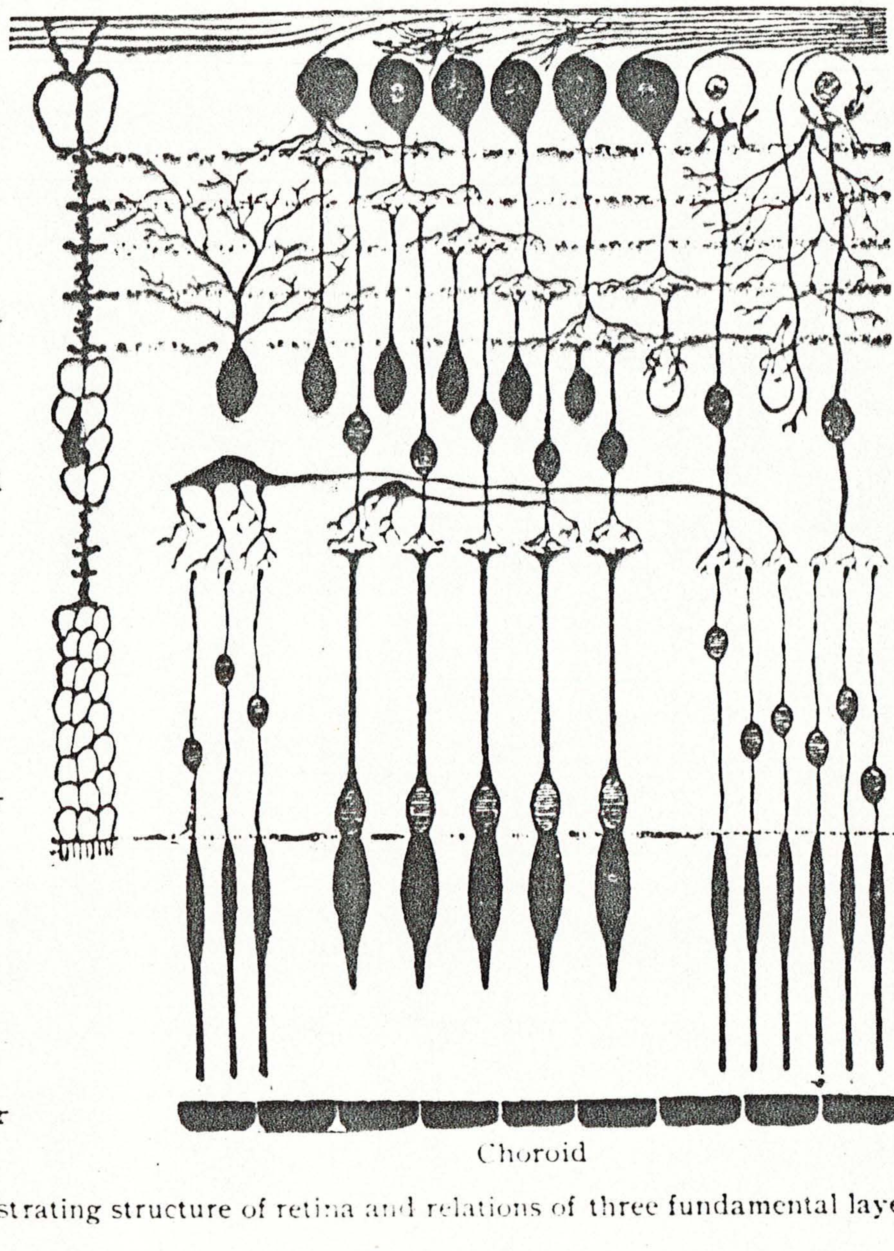


Diagram illustrating structure of retina and relations of three fundamental layers. (*Greeff.*)

[20] Quoted by G. A. Piersol, Human Anatomy, II, 1462.

separate oscillation, oscillate to, and thereby absorb, the bulk of the energy not received in the ganglion fibres. This will render the wavelegth limit at one end of the range for each cone much sharper than would otherwise be the case. Moreover, this absorption might explain the negative after-image if some sort of retentive process, probably chemical, exists in the amacrine cell. The possibility that amacrine cells might play some part in the selectivity of the cones was suggested by Dr. Cook[19], but their specific function, and the possible correspondence between the number of cones and the number of primary color sensations was not mentioned.

A comparison of the rod connections with those of the cones reveals, as Dr. Cook has mentioned, no amacrine cells and no surfaces for a capacity approximating that of the cones. In addition, however, it appears that the resistance, both of the fibres and of the synapses of the rods system must be much greater, not only relative to the inductance and capacity of the rod system itself, but also relative to the resistance of the cone systems.

Before leaving the discussion of Dr. Cook's theory, one additional point seems worthy of mention. One of the most obvious objections to an electromagnetic theory is that no structure resembling the rods and cones can be small enough to have the required inductance and capacity to oscillate to visible wavelengths. This might be over-

19 Dr. S. R. Cook, <u>op. cit.</u>, p. 3.

come by considering that the circuits are in oscillation, not as whole at the fundamental wavelength, but by parts, i. e. to harmonics.

It is not intended that these theoretical speculations should by their specific nature imply any unwarranted certainty. For it is merely with a view to suggesting stimulating, and more or less plausible, possibilities that these have been offered. Nor is it intended that these interesting conjectures should overshadow the points more relevant to the central idea of this discussion, which are the nature and independence of the primary color sensations.

BIBLIOGRAPHY

I. SOURCES

Clark, Janet H., "A Photo-Electric Theory of Color Vision." The Journal of the Optical Society of America, VI, 813, 1922.

Cook, Samuel R., On the Electromagnetic Theory of Sight and Color Vision, May, 1930, unpublished.

von Helmholtz, H., Treatise on Physiological Optics, A translation from the Third German Edition, James P. C. Southall, Translation Editor, 3 vols. The Optical Society of America, n. p., 1924.

Ladd-Franklin, Christine, Color and Color Theories, Harcourt, Brace, and Co., New York, 1929.

Ladd-Franklin, Christine, "Tetra-chromatic Vision and the Genetic Theory of Color." Science, LV, 555.

Ladd-Franklin, Christine, "The Physicist and the Facts of Color." Science, LXVI, 591, 1927.

Shanz, Fritz, "A New Theory of Vision." American Journal of Physiological Optics, IV, 284, 1923.

II. SECONDARY AUTHORITIES

1. Books

Cajori, Florian, A History of Physics, The Macmillan Co., New York, 1922.

Ladd-Franklin, Christine, Color and Color Theories, Harcourt, Brace, and Co., New York, 1929.

Piersol, G. A., Human Anatomy, 2 vols. J. B. Lippincott Co., Philadelphia, n. d., (1908).

Woodworth, R. S., Psychology - A Study of the Mental Life, Henry Holt and Co., New York, 1924.